

# Quark Coalescence in High Energy Collisions

Zi-Wei Lin

*University of Alabama in Huntsville/  
NASA Space Radiation Shielding Program (MSFC)*

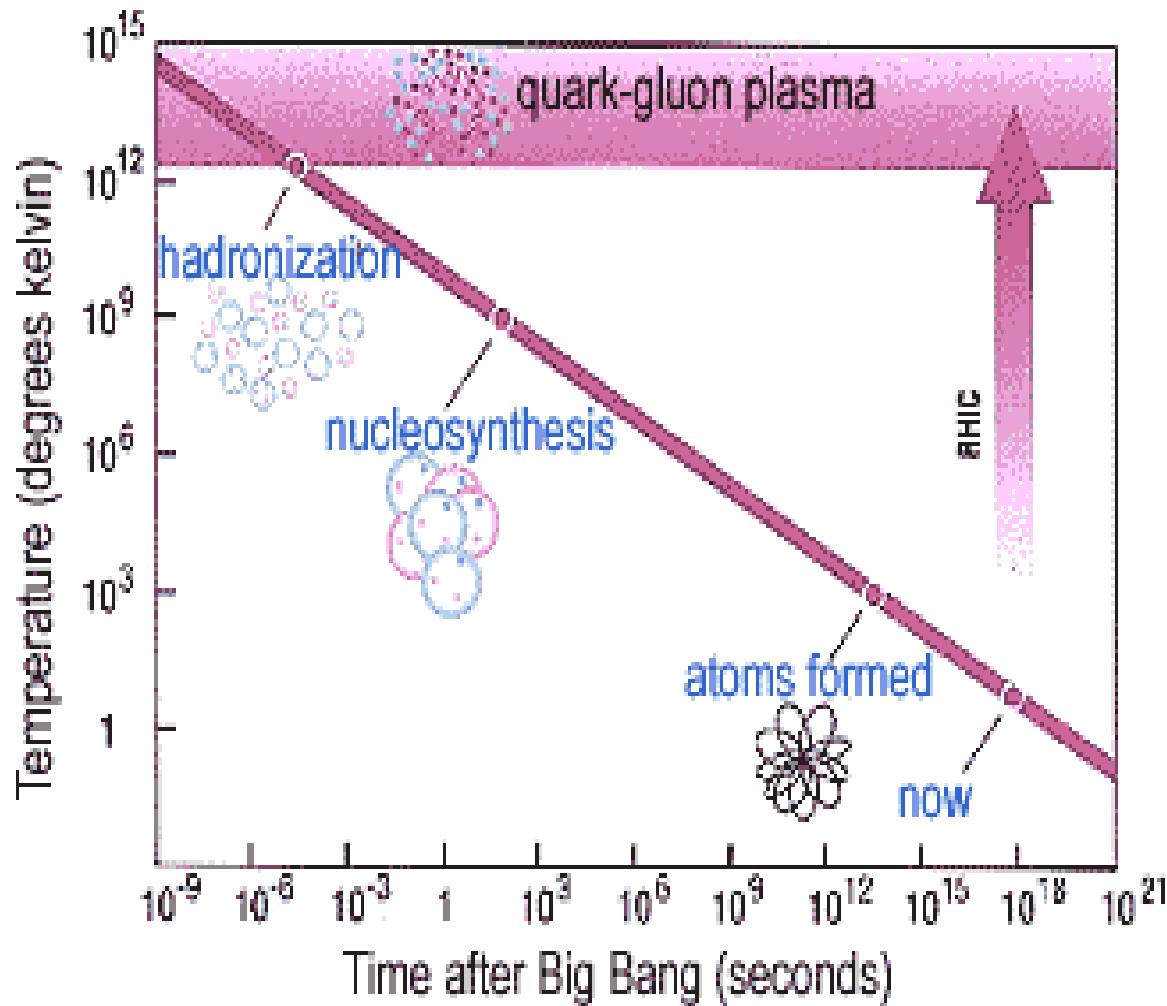
- Introduction to relativistic heavy ion collisions
- Quark coalescence
- Effects on  $v_2$  (azimuthal anisotropy in transverse momentum Pt)
- Have we seen the **QGP** (quark-gluon plasma)?

*This talk is available at*

*<http://nt4.phys.columbia.edu/people/zlin/publications/lin-nsstc04.pdf>*

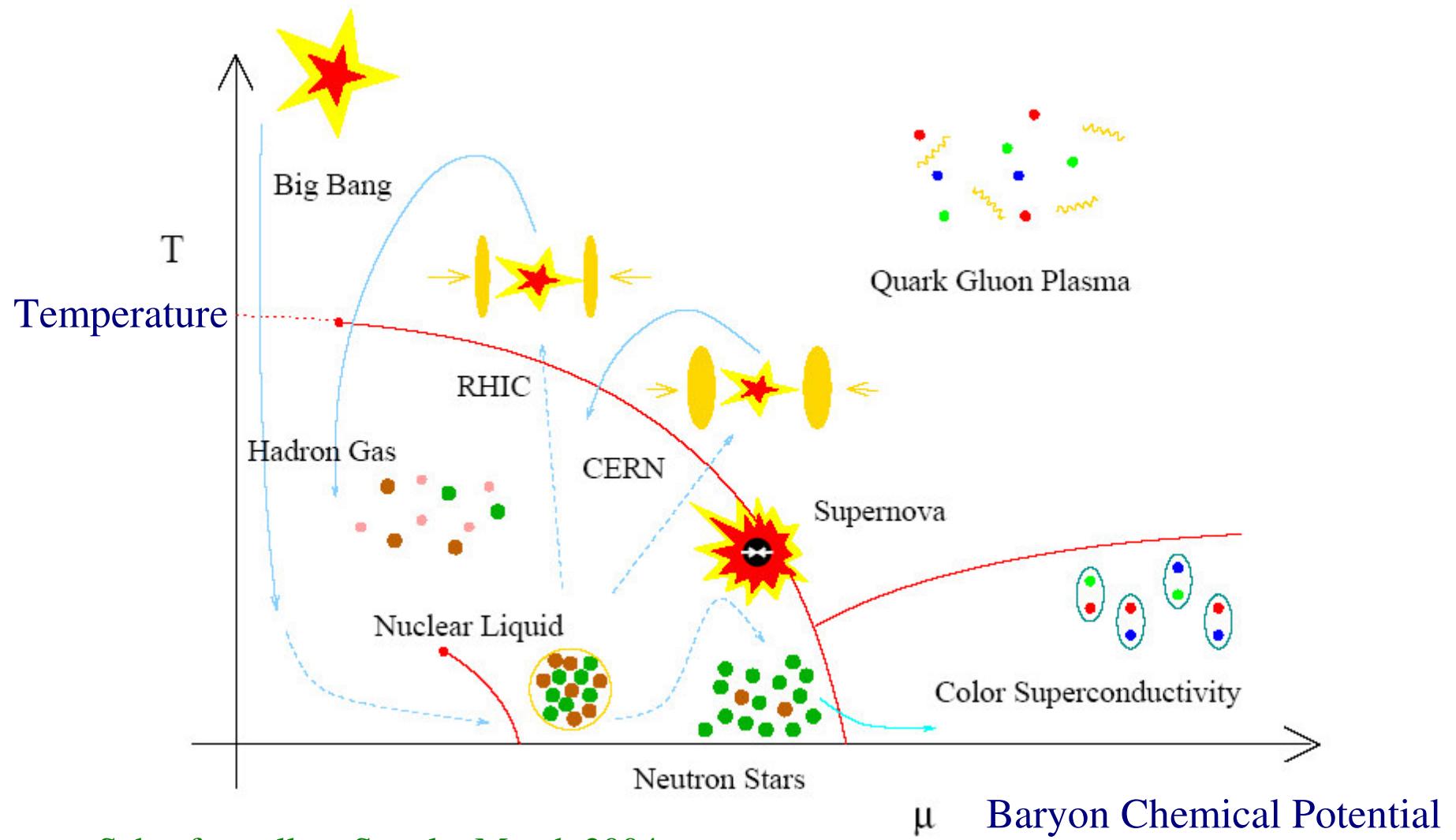


# Time evolution of our universe



from <http://www.bnl.gov/rhic/>





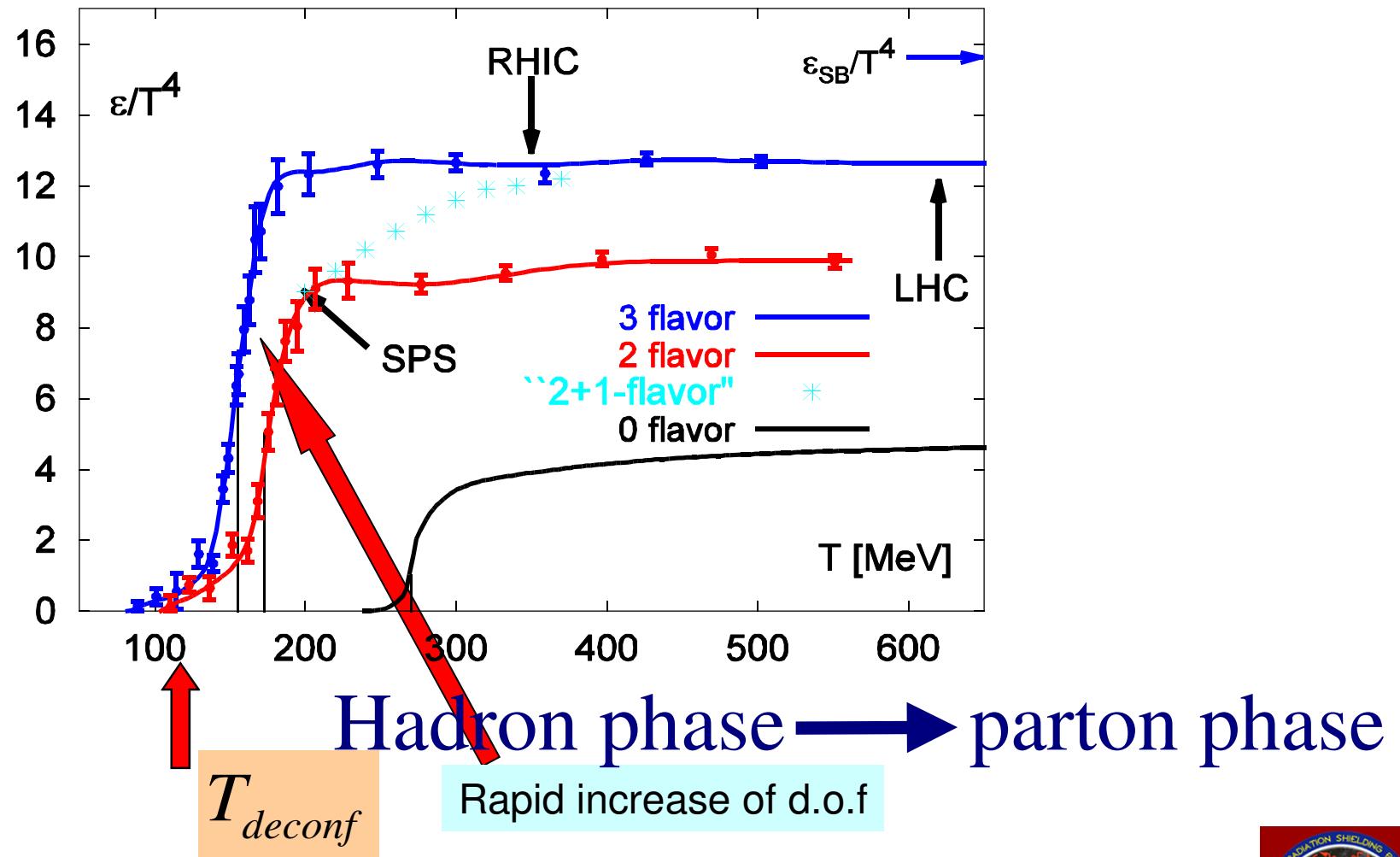
Schaefer, talk at Seattle, March 2004



# Numerical results from 1<sup>st</sup> principles (Lattice QCD)

Deconfinement transition

Petreczky, talk at Skopelos, Hellas, May 2004



# Recognition of QCD from Sweden on 10/05/2004



## The Nobel Prize in Physics 2004

"for the discovery of asymptotic freedom in the theory of the strong interaction"



photo PRB



photo PRB

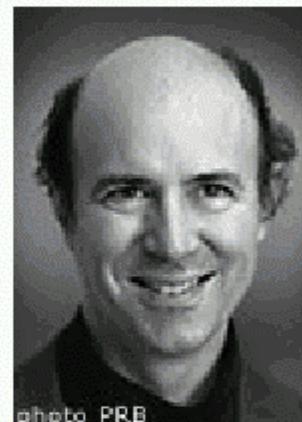


photo PRB

### **David J. Gross**

1/3 of the prize

USA

Kavli Institute for  
Theoretical Physics,  
University of  
California  
Santa Barbara, CA,  
USA

### **H. David Politzer**

1/3 of the prize

USA

California Institute of  
Technology  
Pasadena, CA, USA

### **Frank Wilczek**

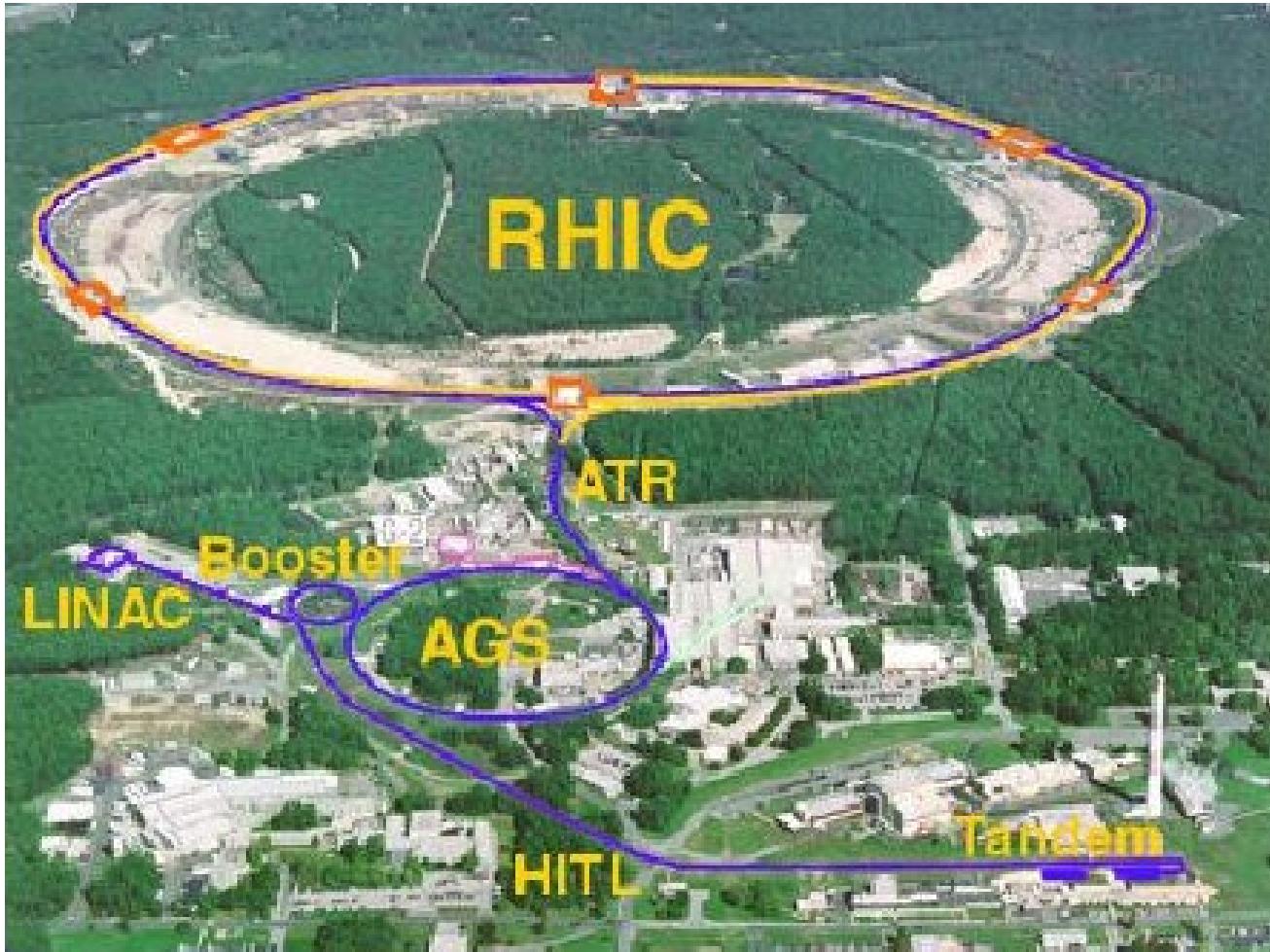
1/3 of the prize

USA

Massachusetts  
Institute of  
Technology (MIT)  
Cambridge, MA, USA



# RHIC (Relativistic Heavy Ion Collider) at Brookhaven National Laboratory



Au+Au collisions up to 200AGeV  
High energy density/temperature ~ universe 1ms after the Big Bang



# Goal of relativistic heavy ion physics

Relativistic Heavy Ion  
Machines

Sqrt(s) (AGeV)

Main Beam

CERN-SPS (past)

8-17

Pb+Pb

BNL-RHIC (now)

~20-200

Au+Au

CERN-LHC (future)

up to 5500

Pb+Pb

$$\epsilon_0 \sim \frac{dE_T/dy}{\pi R^2 \tau_0} \simeq \frac{dE_T/dy}{150 fm^3}$$

$\sim 2.5$       6      20 GeV/fm<sup>3</sup>  
SPS      RHIC200      LHC

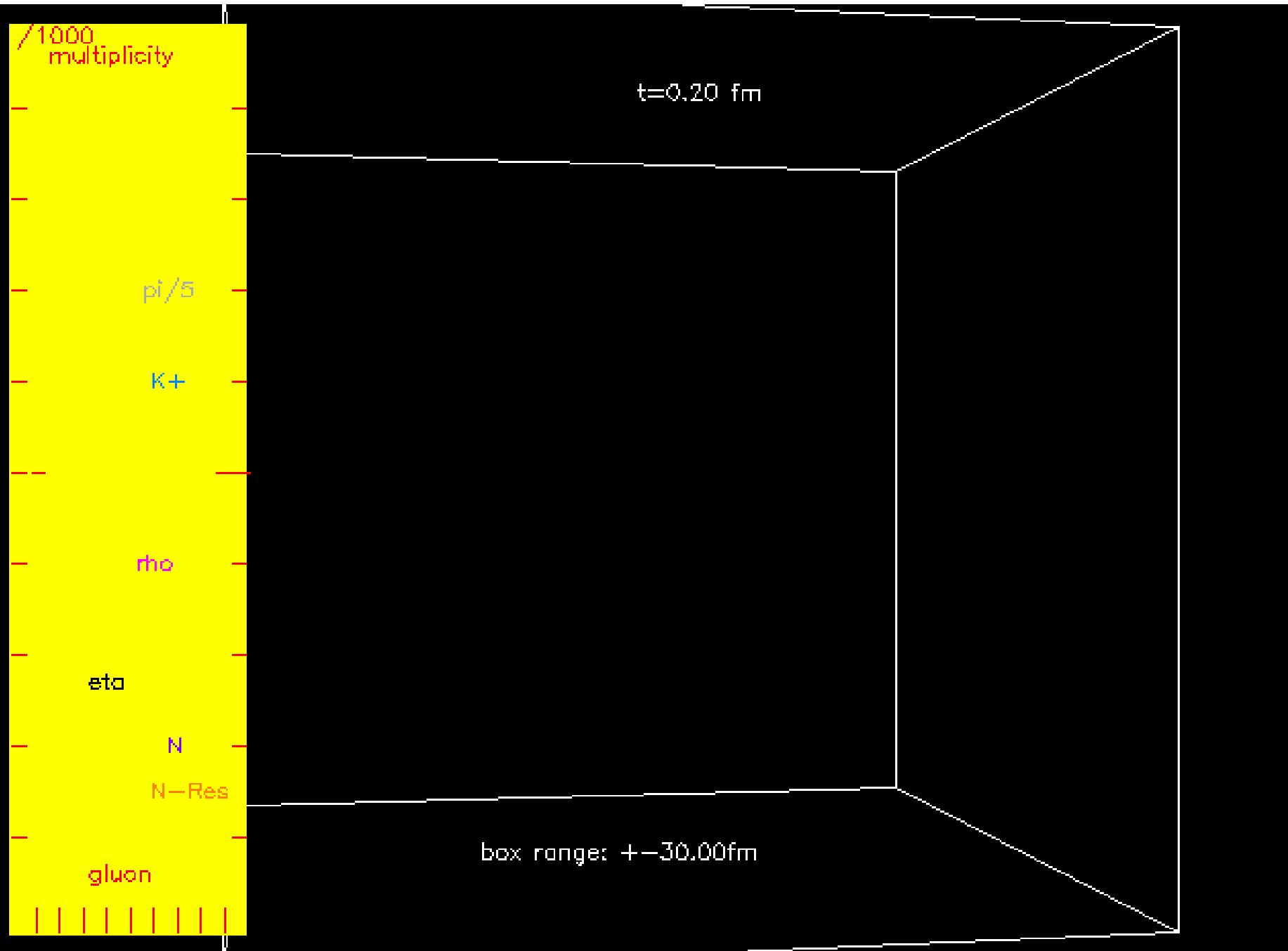
proper formation  
time, take 1fm/c

Study properties of partonic and hadronic matter  
and Quantum ChromoDynamics (QCD)



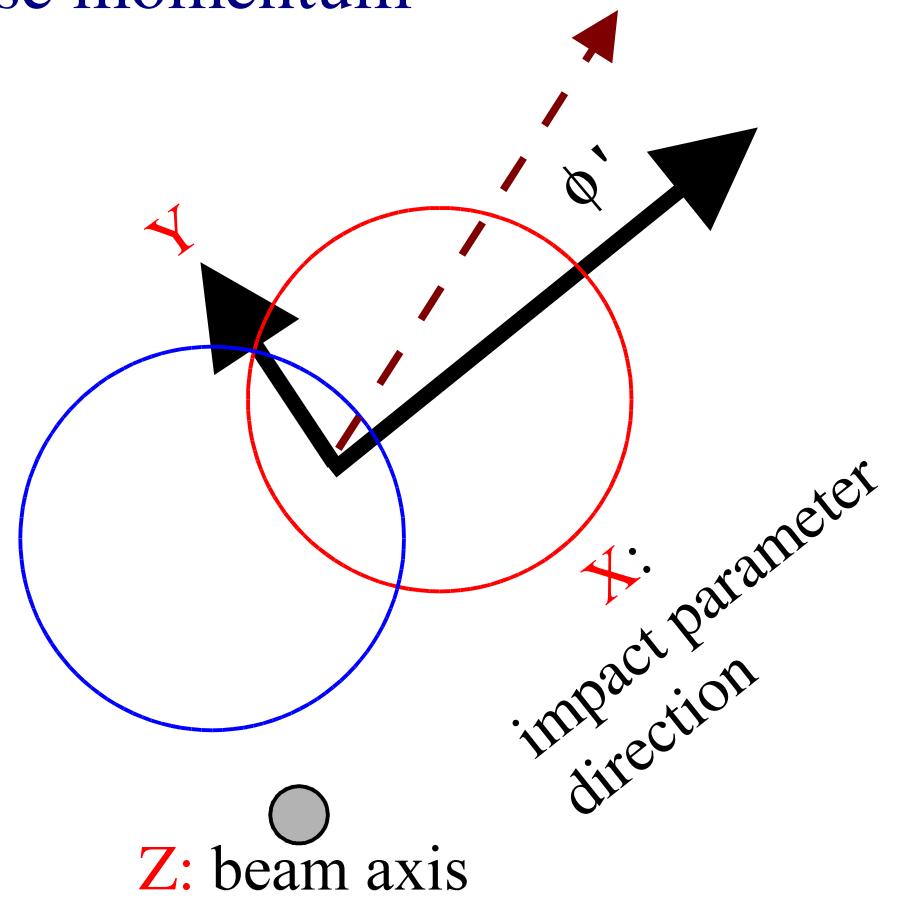
# A Central Au+Au Event at RHIC from A Multi-Phase Transport (AMPT)

Zhang et al., PRC61(00)  
ZWL et al., PRC64(01)  
ZWL et al., PRC68(03)  
.....



# Elliptic flow ( $v_2$ ): azimuthal anisotropy in transverse momentum

$$v_2 = \langle \cos(2\phi') \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$



*non-central collisions*

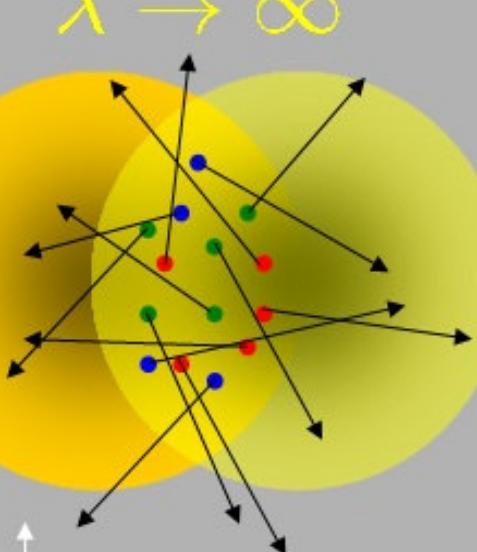
# Elliptic Flow( $v_2$ ) Ollitrault, PRD46 (92)

Hirano, talk at Hot Quarks, July 2004

How does the system respond to initial spatial anisotropy?

Free streaming

$$\lambda \rightarrow \infty$$

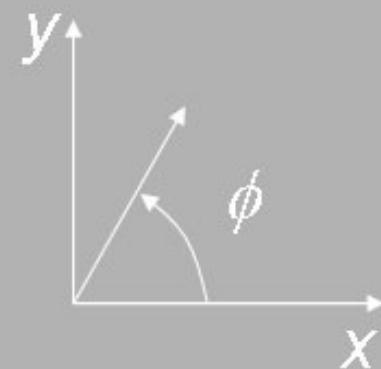


$$dN/d\phi$$

$$0$$

$$\phi$$

$$2\pi$$



INPUT

Initial spatial  
anisotropy

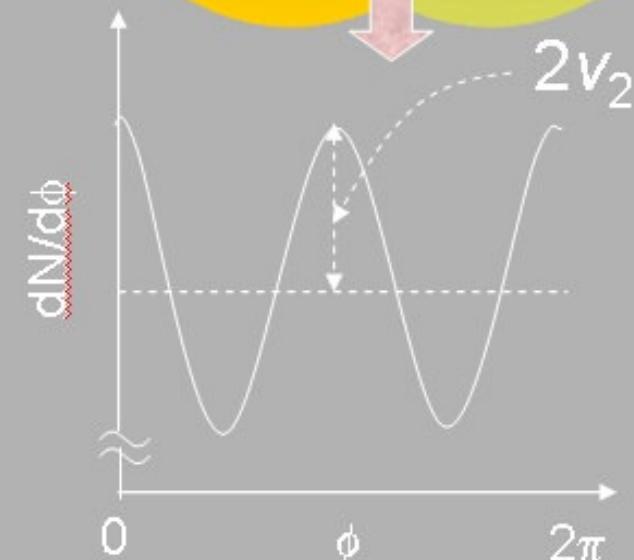
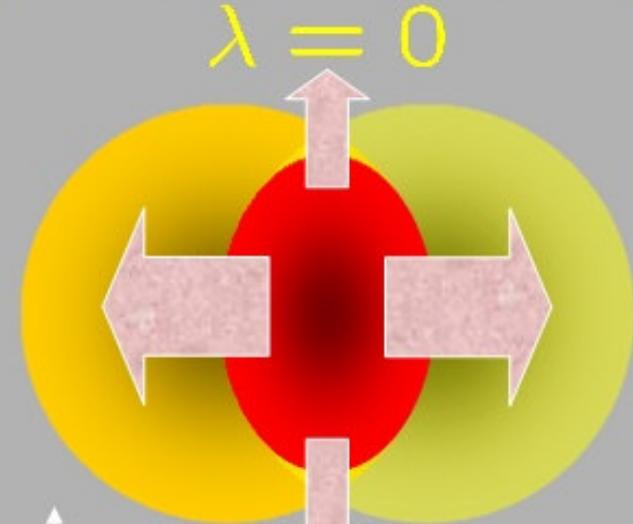
Rescattering

OUTPUT

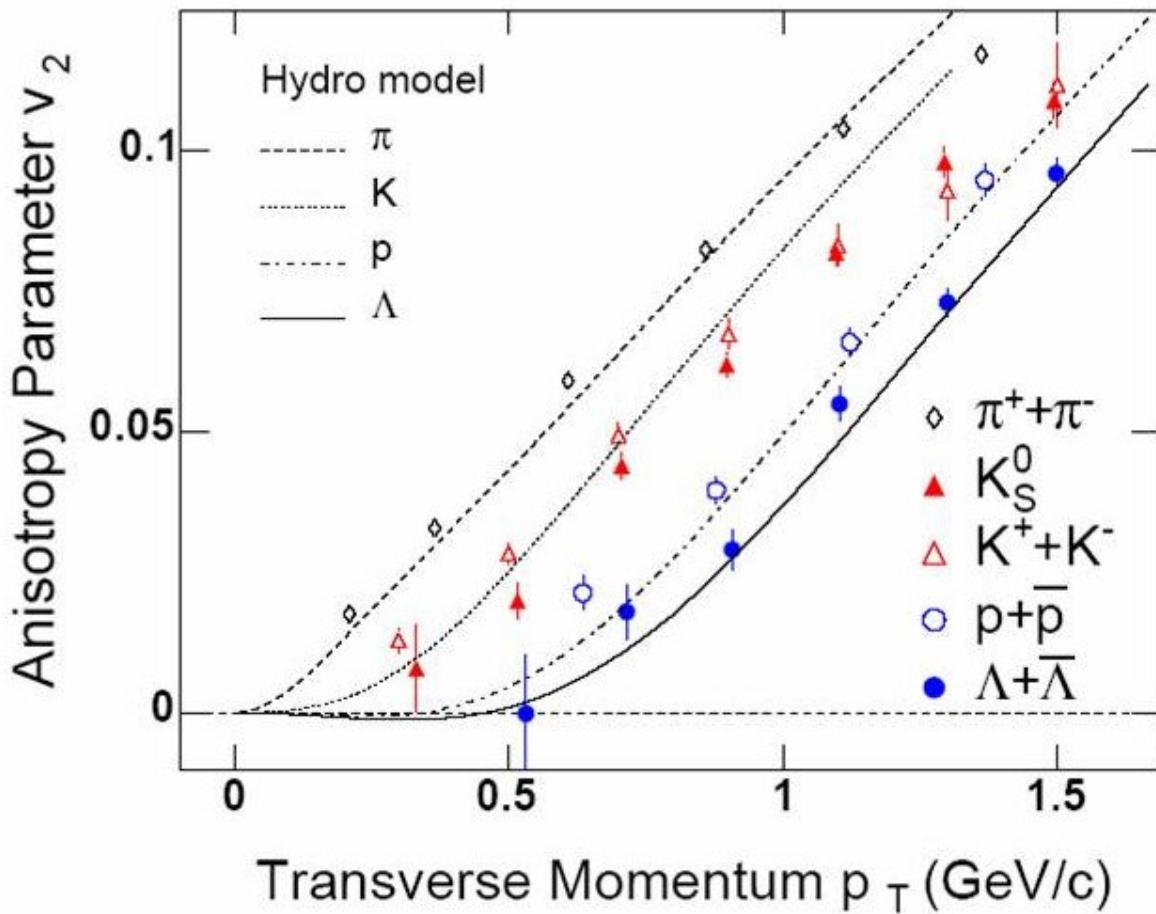
Final momentum  
anisotropy

Hydrodynamic expansion

$$\lambda = 0$$



# $v_2$ (low Pt): RHIC data



follow  
mass ordering:  
 $v_2(M) < v_2(m)$   
for  $M > m$

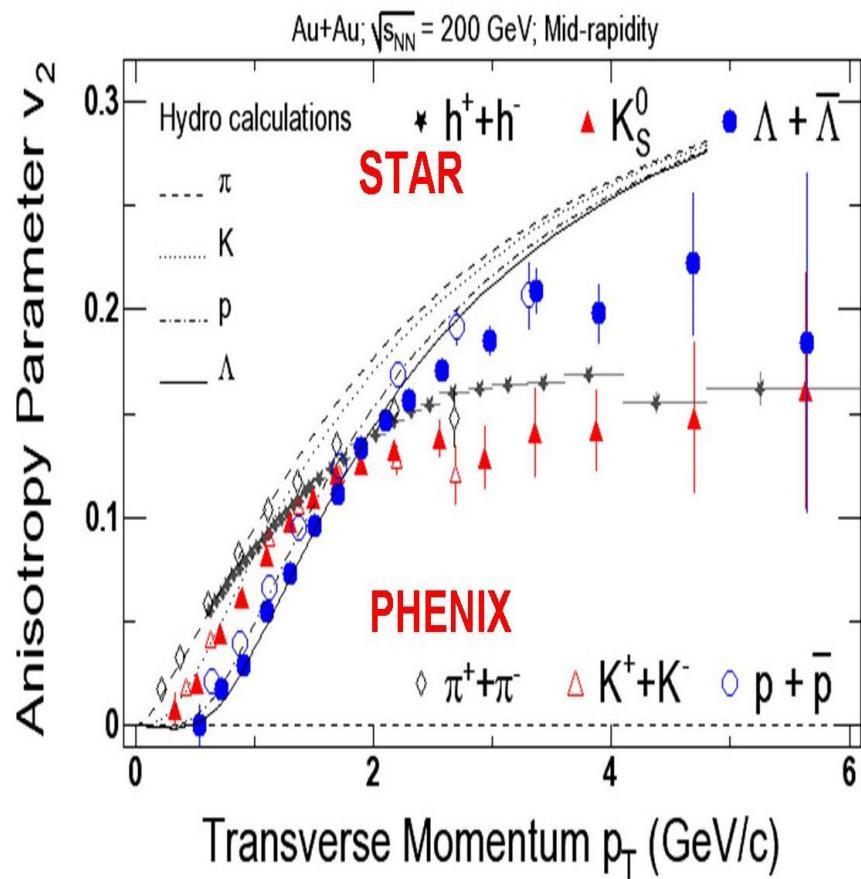
Huovinen et al, PLB503(01)

PHENIX, NPA715(03)



# $v_2$ (high Pt): RHIC data

Huang, talk at Skopelos, Hellas, May 2004

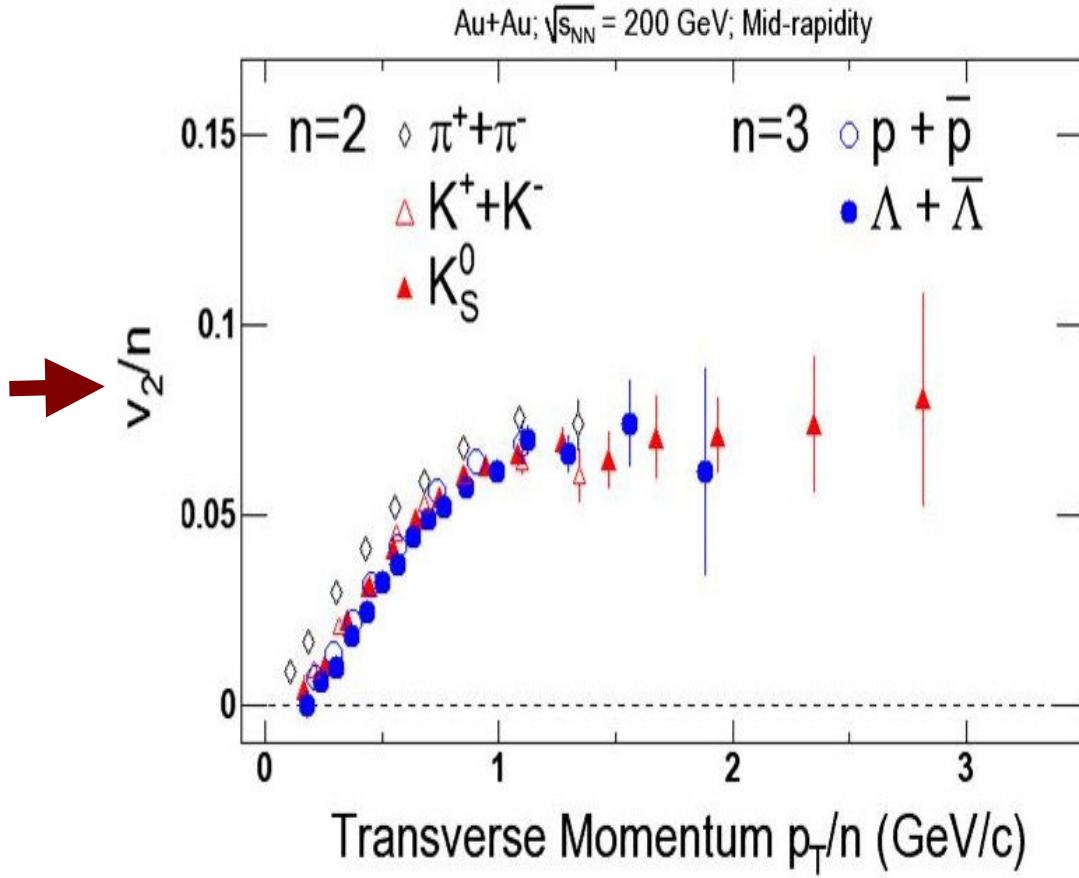
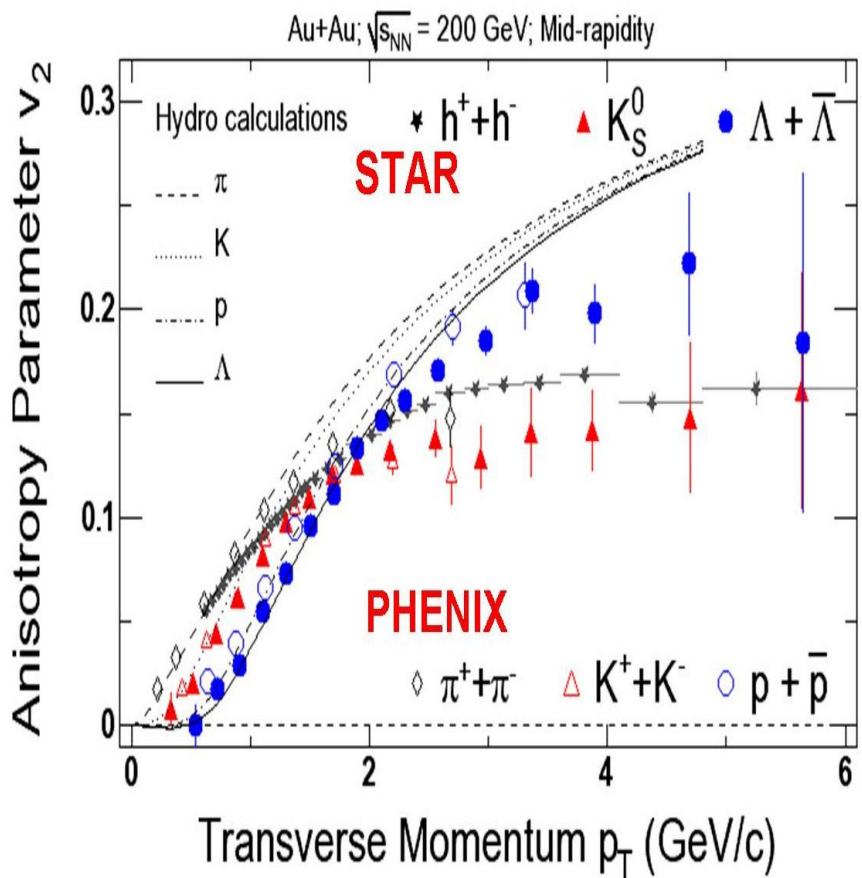


NO mass ordering at high Pt



# v2 data after scaling

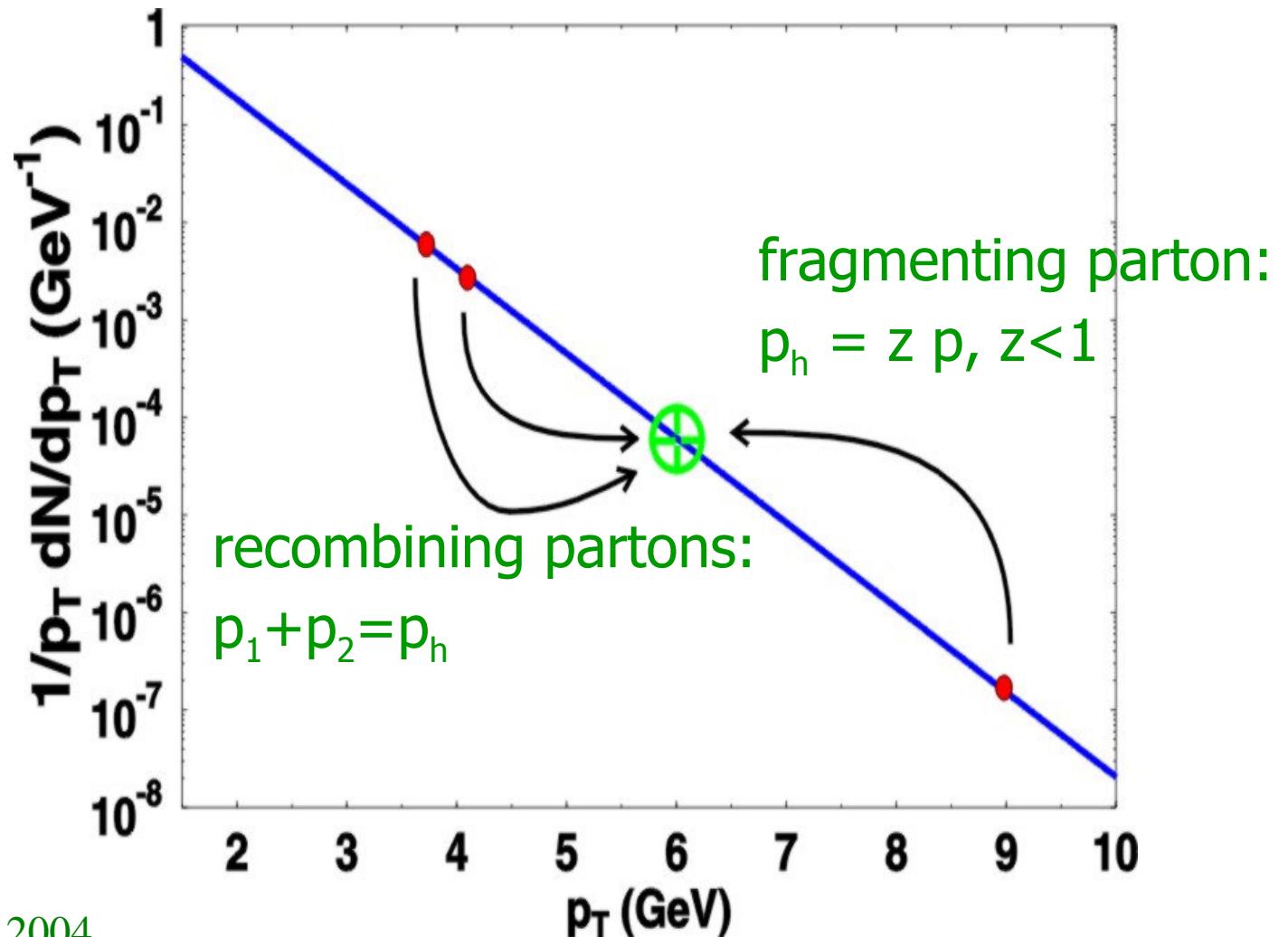
Huang, talk at Skopelos, Hellas, May 2004



*Simple scaling works !*



# Scaling from Quark Coalescence



Fries, Quark Matter 2004



# The Coalescence Model first used for deuteron productions:



Butler&Pearson, PR129(63);  
Sato&Yazaki, PLB98 (81);  
Gyulassy, Frankel&Remler, NPA402(83);  
Dover et al, PRC44(91);  
Scheibl&Heinz, PRC59(99);  
...



# Applications to Heavy Ion Collisions:

**ALCOR** (ALgebraic COalescence Rehadronization) model:

Hadron multiplicities:

Biro,Levai&Zimanyi, PLB347(95); JPG28(02); ...

**AMPT** (A Multi-Phase Transport) model:

v2 (Pt: 0-2 GeV): ZWL&Ko, PRC65(02)

pion HBT: ZWL,Ko&Pal, PRL89(02)

v4, v6, ...: Chen,Ko&ZWL, PRC69(04)

Flavor ordering of v2 at high Pt: ZWL&Ko, PRL89(02)

**Amplification of quark v2 and ordering:**

Voloshin, NPA715(03); Molnar&Voloshin, PRL91(03);

ZWL&Molnar, PRC68(03); Greco,Ko&Levai,PRC68(03); ...

**Enhanced p/pi ratio:**

Hwa&Yang, PRC65(02); Fries et al, PRL90(03); Greco,Ko&Levai, PRL90(03); ...



# The Quark Coalescence Model

Near hadronization, gluons may decouple (serve to "dress" quarks), consider only constituent quarks for hadronization.

$\alpha\beta \rightarrow M :$

$$E \frac{dN_M(\vec{p})}{d^3 p} = d_M \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3 q |\psi_{\vec{p}}(\vec{q})|^2 f_\alpha(\vec{p}_\alpha, x) f_\beta(\vec{p}_\beta, x)$$

$\alpha\beta\gamma \rightarrow B :$

$$E \frac{dN_B(\vec{p})}{d^3 p} = d_B \int \frac{d\sigma^\mu p_\mu}{(2\pi)^3} \int d^3 q_1 d^3 q_2 |\psi_{\vec{p}}(\vec{q}_1, \vec{q}_2)|^2 f_\alpha(\vec{p}_\alpha, x) f_\beta(\vec{p}_\beta, x) f_\gamma(\vec{p}_\gamma, x)$$

*hadronization  
hypersurface*

*hadron wavefunction*

*quark distributions*

Already assumed:

rare process, small binding energy, factorization of 2-parton distribution functions, slowly-varying quark spatial-distributions, same hypersurface



# Mass effect in quark coalescence:

ZWL&Molnar, PRC68(03)

*how much high-Pt hadron momentum is carried by each valence quark?*

1) Meson in the rest-frame:

$$-\vec{q}_i' \quad \vec{q}_i' \quad E_i' \equiv \sqrt{m_i^2 + |\vec{q}_i'|^2}$$

2) In LAB frame:

$$\vec{p}_{\perp} \equiv p_{\perp} \vec{n}_{\perp}$$

$$p_{\perp i} = \frac{E_i'}{m_M} p_{\perp} + \vec{q}_i' \cdot \vec{n}_{\perp} \frac{\sqrt{p_{\perp}^2 + m_M^2}}{m_M}$$

If  $(\vec{q}_i')^2 \ll m_i^2$  and  $m_M \approx m_\alpha + m_\beta$  (small binding energy):

Define  $z_i \equiv \frac{p_{\perp i}}{p_{\perp}}$

$$\bar{z}_i = \frac{m_i}{m_\alpha + m_\beta}$$



# v2 with mass effects

ZWL&Molnar, PRC68(03)



$$\bar{z}_i = \frac{m_i}{m_\alpha + m_\beta}, \quad \bar{z}_i = \frac{m_i}{m_\alpha + m_\beta + m_\gamma}$$

Meson
Baryon

→

$$v_2^M(p_\perp) = \frac{\overline{v_{2,\alpha}} + \overline{v_{2,\beta}}}{1 + 2 \frac{\overline{v_{2,\alpha}}}{\overline{v_{2,\beta}}}} \simeq \overline{v_{2,\alpha}} + \overline{v_{2,\beta}},$$

$$v_2^B(p_\perp) = \frac{\overline{v_{2,\alpha}} + \overline{v_{2,\beta}} + \overline{v_{2,\gamma}} + 3 \frac{\overline{v_{2,\alpha}}}{\overline{v_{2,\beta}}} \frac{\overline{v_{2,\beta}}}{\overline{v_{2,\gamma}}}}{1 + 2 (\overline{v_{2,\alpha}} \overline{v_{2,\beta}} + \overline{v_{2,\alpha}} \overline{v_{2,\gamma}} + \overline{v_{2,\beta}} \overline{v_{2,\gamma}})} \simeq \overline{v_{2,\alpha}} + \overline{v_{2,\beta}} + \overline{v_{2,\gamma}}$$

$$\overline{v_{2,i}} \equiv v_{2,i}(\bar{z}_i p_\perp)$$

for identical quark mass:  
Molnar &Voloshin, PRL91(03)



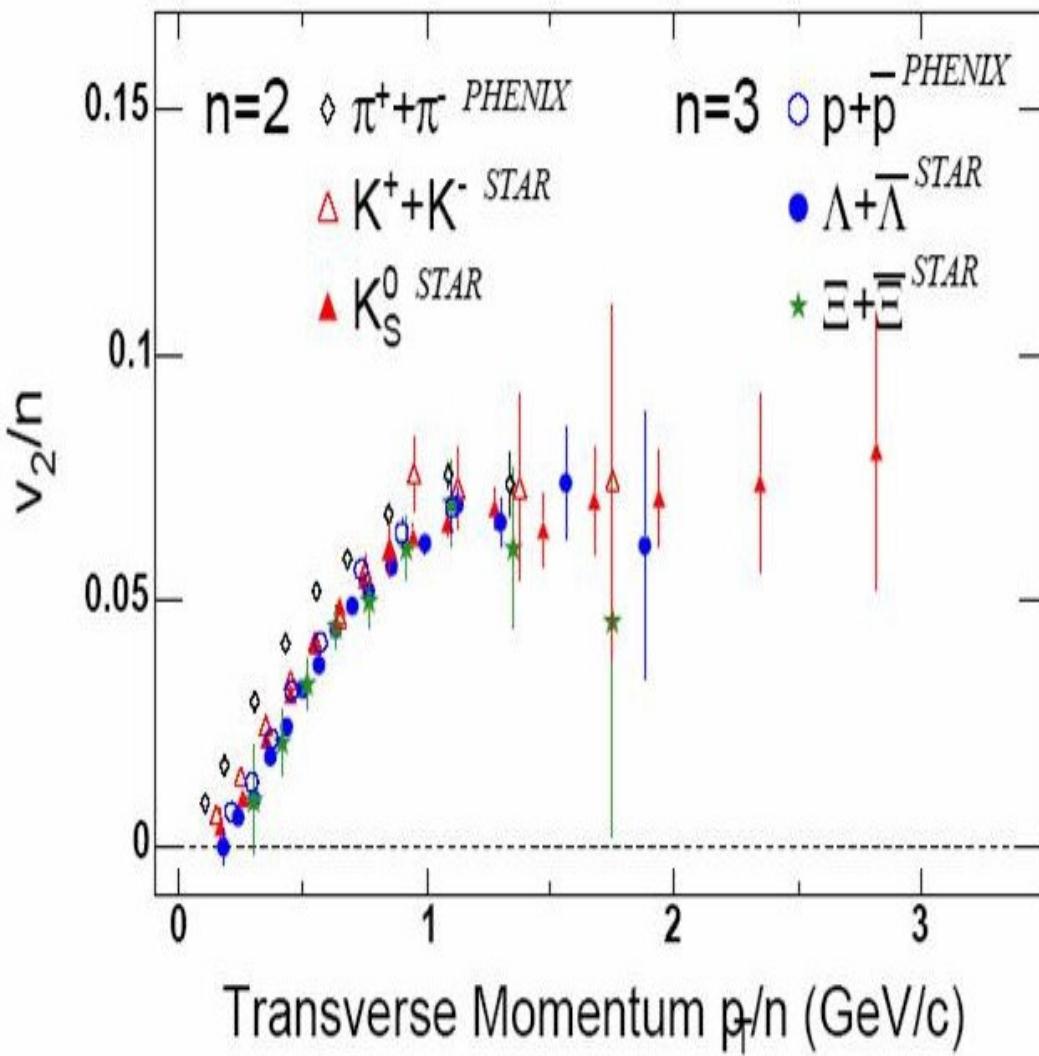
$$z_1 = z_2 = z_3$$

$$v_2^M(p_\perp) \simeq 2v_2^q(p_\perp/2)$$

$$v_2^B(p_\perp) \simeq 3v_2^q(p_\perp/3)$$

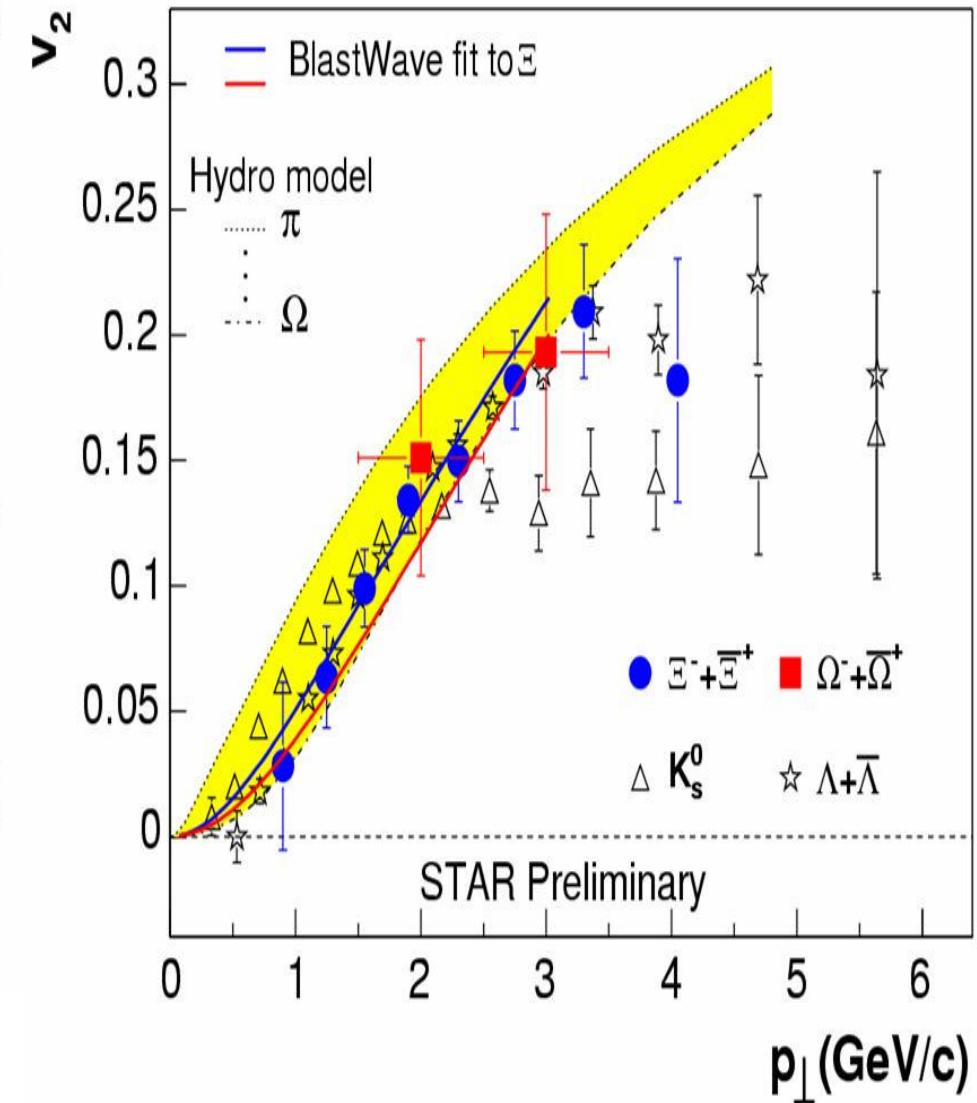


# More comparisons of scaling with RHIC v2 data



$$v_2^M(p_\perp) \simeq 2v_2^q(p_\perp/2)$$

$$v_2^B(p_\perp) \simeq 3v_2^q(p_\perp/3)$$



# charm v2 with mass effects:

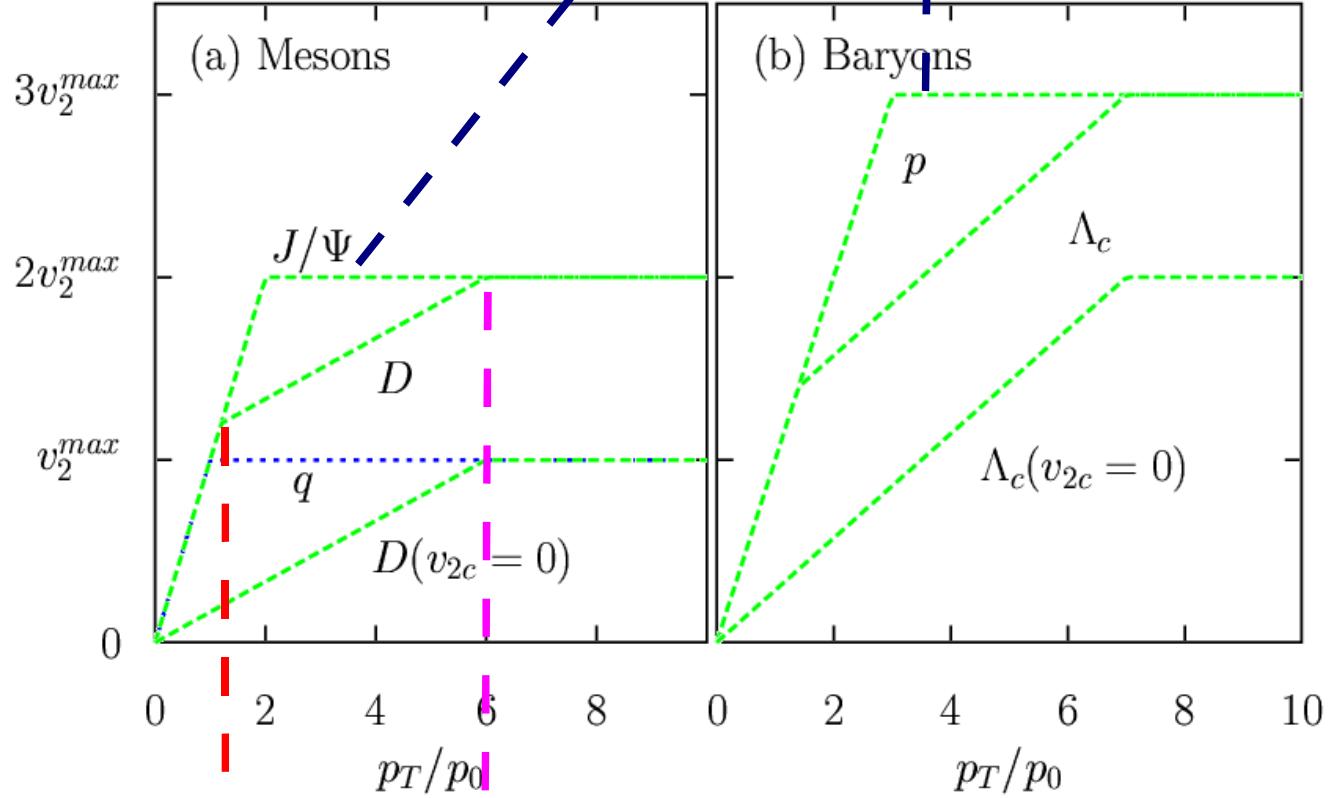
$$m_c/m_q=5$$

$$v_2^D(p_\perp) \simeq v_2^c \left( \frac{5}{6} p_\perp \right) + v_2^q \left( \frac{1}{6} p_\perp \right)$$

*equal quark mass:*

Example:

$$v_{2,c}(p_\perp) = v_{2,q}(p_\perp)$$



*different quark mass:*

charm quark in  $D$  saturates at  $P_T=6P_0/5$

light quark in  $D$  saturates at  $P_T=6P_0$



# Has the Quark-Gluon Plasma been discovered at RHIC??

Zi-Wei Lin

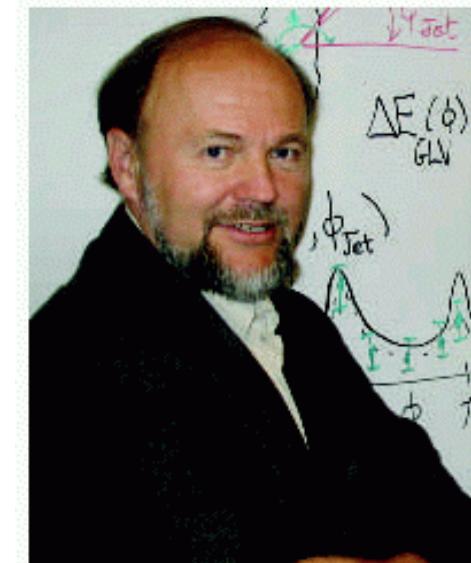
Oct 8, 2004

UAH / NASA Space Radiation Shielding Program MSFC

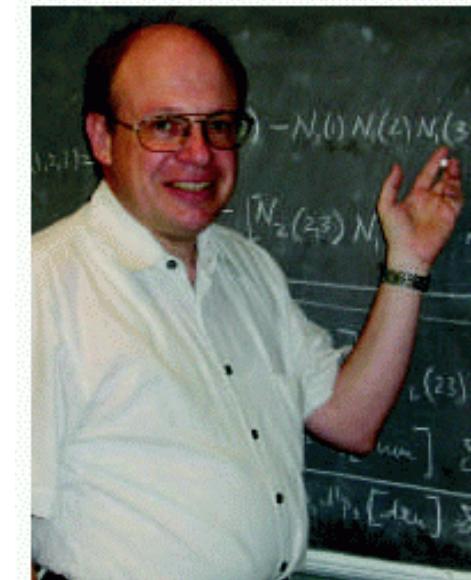


# Has the Quark-Gluon Plasma been discovered at RHIC??

Nature 430 (2004)



Theorists Miklos Gyulassy (above) and Ulrich Heinz believe that a quark-gluon plasma has been created.



# Has the Quark-Gluon Plasma been discovered at RHIC??

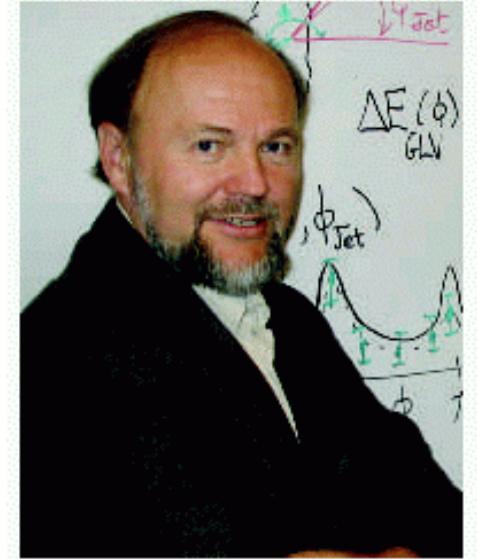
Nature 430 (2004)



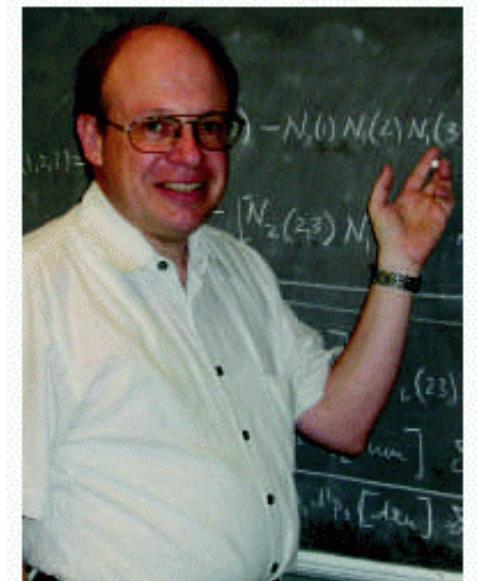
Experimentalists at RHIC want more data before naming the new form of matter they have generated.

the PHENIX collaboration

experimentalists  
↓  
theorists



Theorists Miklos Gyulassy (above) and Ulrich Heinz believe that a quark-gluon plasma has been created.



# One theorist's point of view (from Gyulassy, Quark Matter 2004):

$$\begin{aligned} \text{QGP} &= \text{Bulk Collective} + \text{Parton Dynamic} + \text{Discriminator} \\ &= P_{\text{QCD}} + p\text{QCD} + dA \\ &= v_n(p_T, m) + (R+I)_{AA} + (R+I)_{DA} \end{aligned}$$

1                    2                    3

- 1) Evidence for  $P_{\text{QCD}}$  via  $v_n$  bulk collective flow of  $10^4 \pi, K, p, \dots$
- 2) Evidence for pQCD jet quenching in Au+Au at RHIC
- 3) Evidence jet *un*-quenching in D+Au = Null Control

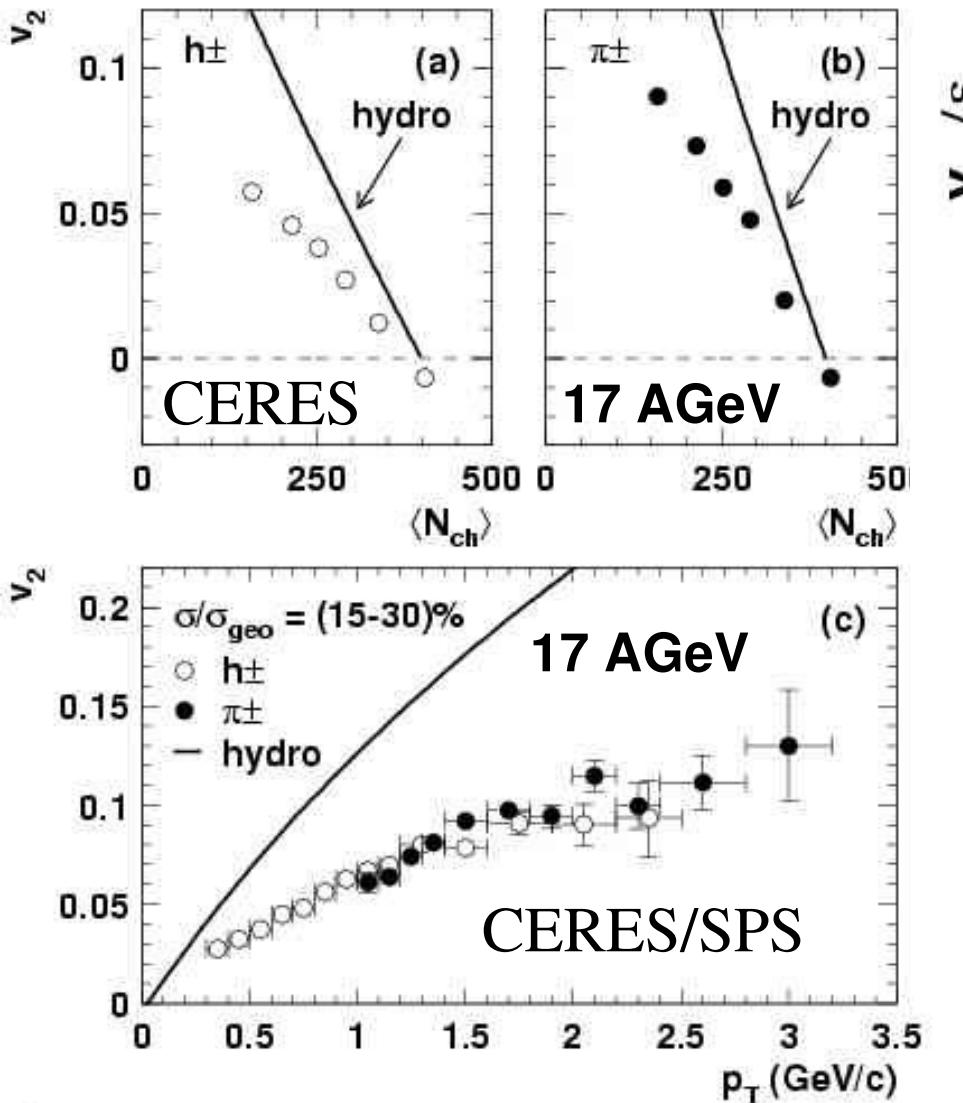
**2+3 are necessary but 1 is critical for sufficiency !**

**My conclusion: “overwhelming evidence” at QM04  
that QGP Bulk Matter is made in AuAu at 200 AGeV**

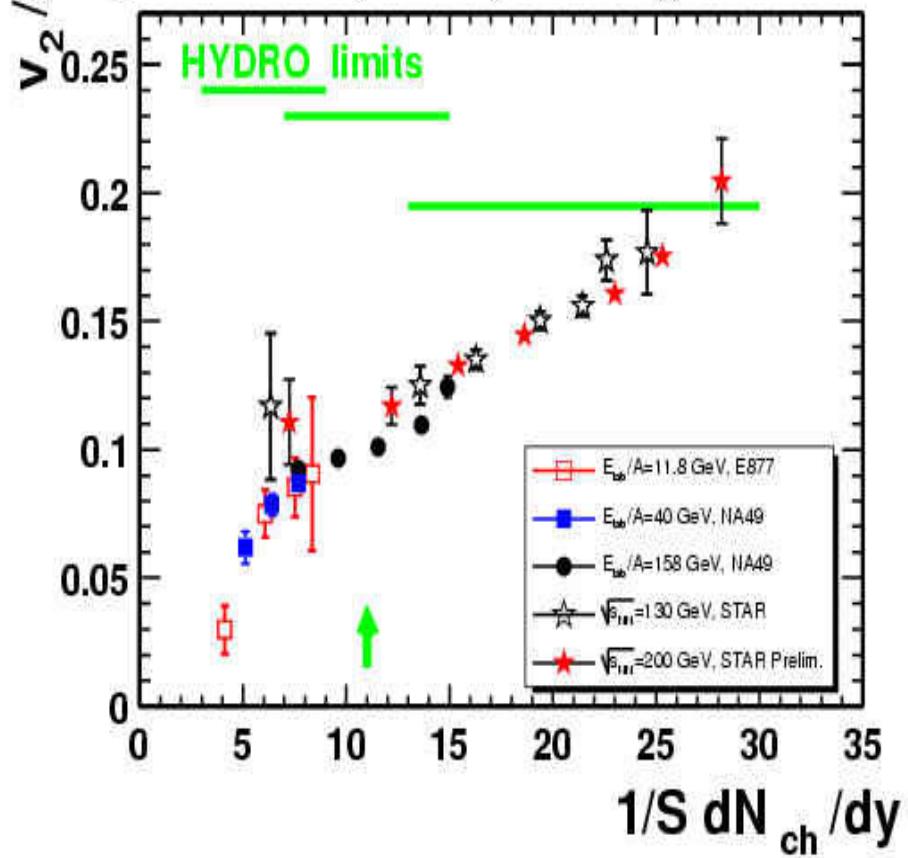


# 1 : Below RHIC energies, Bulk Flow does not reach QGP hydro!

from Gyulassy, Quark Matter 2004

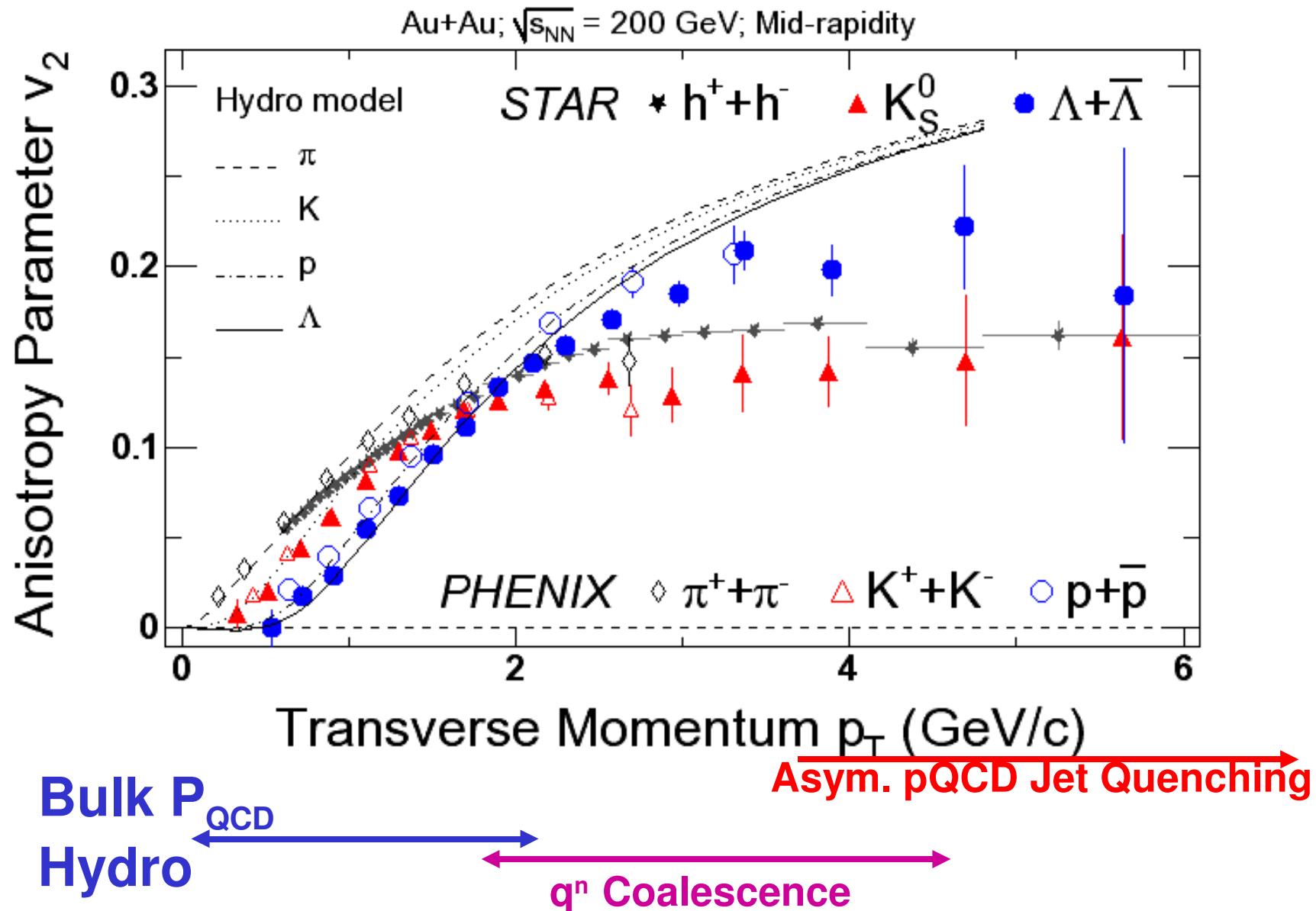


2) DIRECTED AND ELLIPTIC FLOW OF CHARGED PIONS AND PROTONS IN PB + PB COLLISIONS AT 40-A-GeV AND 158-A-GeV.  
By NA49 Collaboration (C. Alt *et al.*). Mar 2003. 35pp.

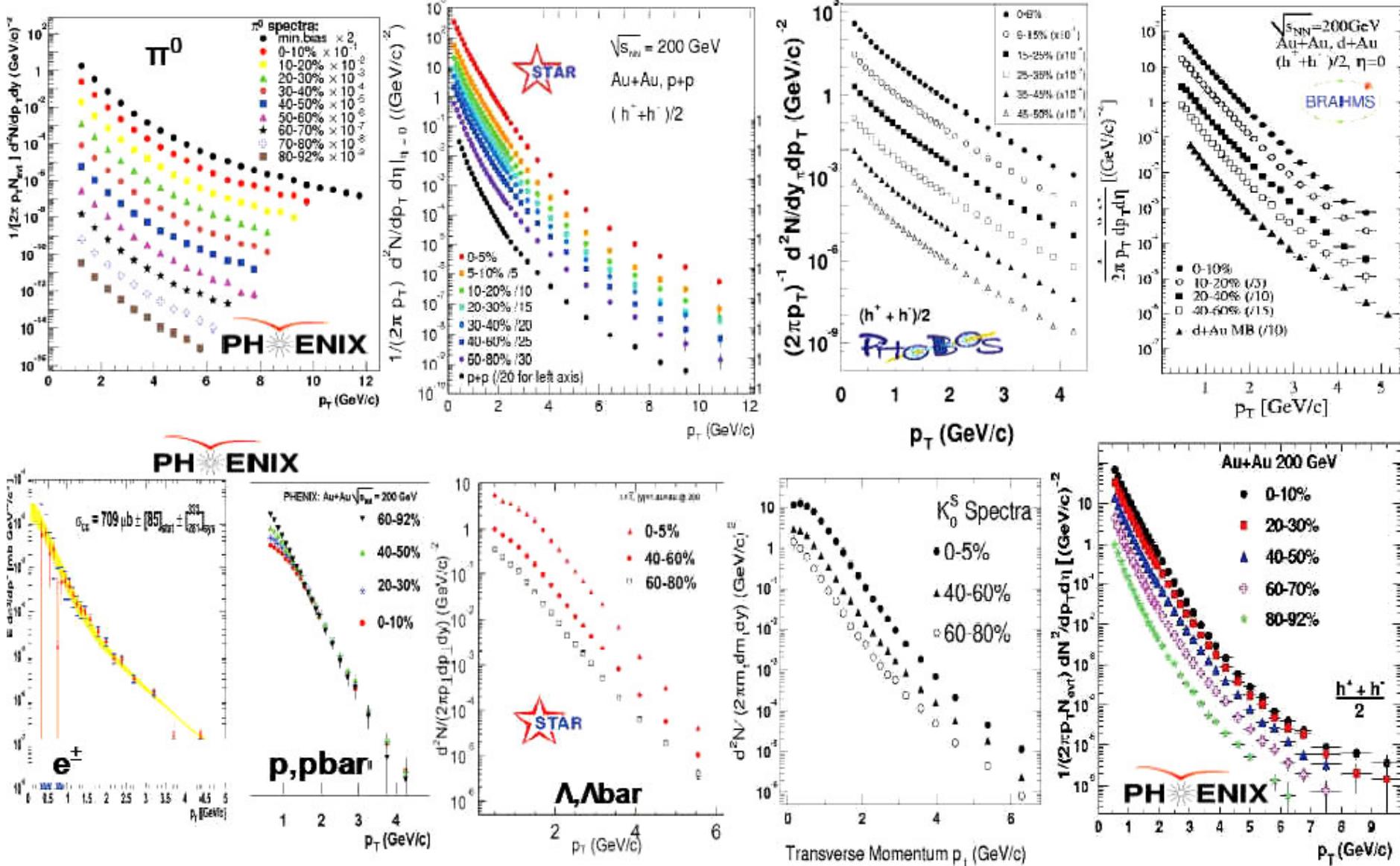


# 1 :The QGP Fingerprint at RHIC = Bulk collective flow $P_{\text{QCD}}(T)$

from Gyulassy, Quark Matter 2004



## High $p_T$ spectra in Au+Au @ 200 GeV



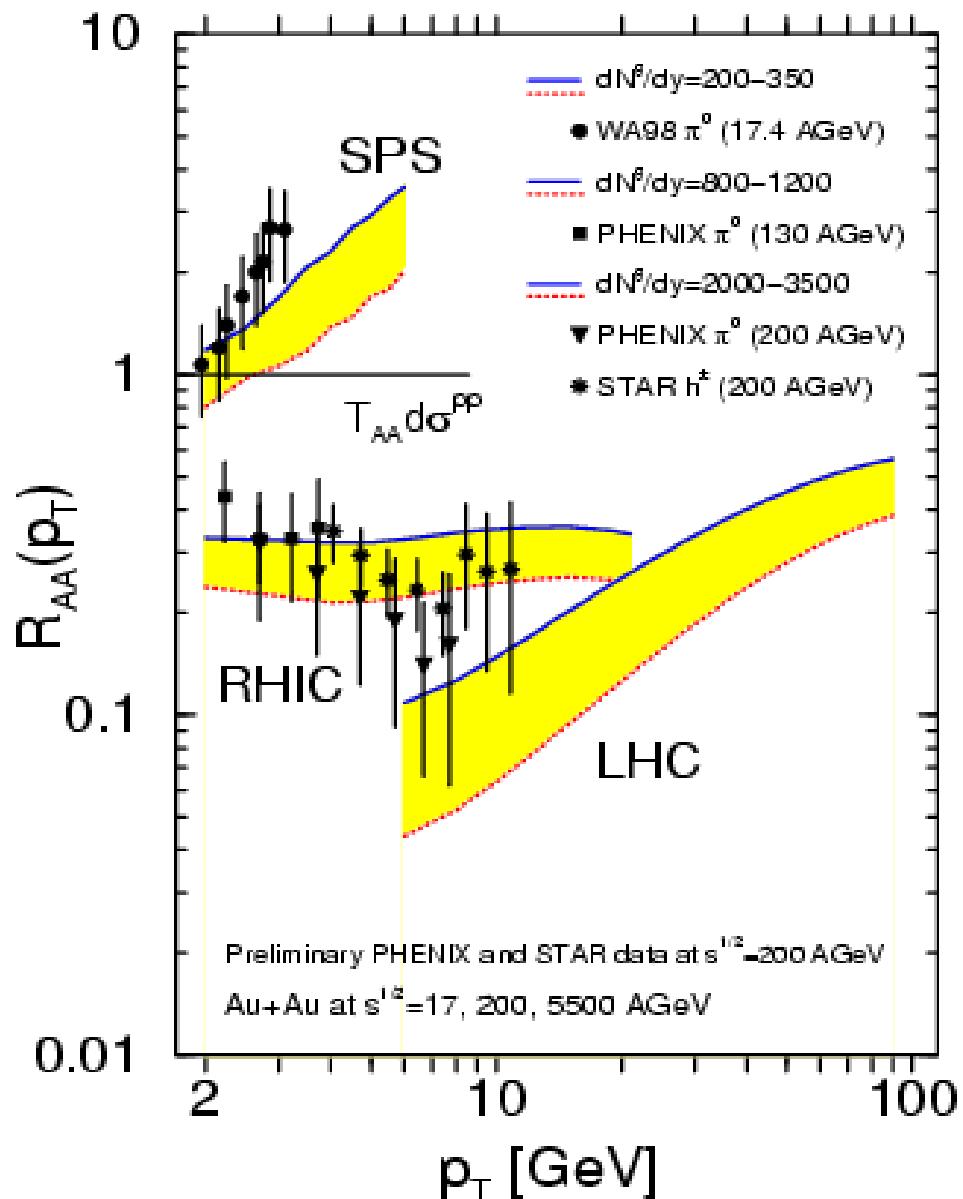
Quark Matter 2004, Oakland, Jan. 14, 2003

David d'Enterria (Columbia Univ.)



## 2 : Single Hadron Tomography from SPS, RHIC, LHC

Ivan Vitev and M.G, Phys.Rev.Lett. 89 (2002)



Cronin dominates at SPS

Cronin+Quench+Shadow  
conspire to give ~ flat  
suppression out to highest pT  
at RHIC with  $R \sim N_{\text{part}}/N_{\text{bin}}$



For now, it seems that both sides are trapped in a stalemate. Zajc hesitates to give a precise date for when, or even if, a QGP discovery will be announced at RHIC. “We’re still collecting evidence, and I think we’re making good progress,” he says. But the theorists say that the days of QGP are already here. “The evidence is overwhelmingly clear,” Gyulassy says. “It’s time we gave it a name.” ■

**Geoff Brumfiel is *Nature's* Washington physical sciences correspondent.**

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*One main reason:  
so far we have not clearly “seen” parton degrees of freedom*



# What could quark coalescence model tell us about QGP?

For hadrons with narrow wavefunction (e.g., D &  $\Lambda_c$ ), one can

**Unfold quark  $v_2(p_t)$**

from hadron elliptic flow:

$$v_2^q(p_\perp) = v_2^{\Lambda_c}((2+r)p_\perp) - v_2^D((1+r)p_\perp)$$

$$v_2^c(p_\perp) = 2v_2^D\left(\frac{1+r}{r}p_\perp\right) - v_2^{\Lambda_c}\left(\frac{2+r}{r}p_\perp\right)$$

$$r \equiv \frac{m_c}{m_q}$$

3-8 inputs,

but have many hadron species (~10 to 30) to check these relations:

→ *parton degrees of freedom?*



# Summary

- Quark coalescence provides a possible hadronization model
- So far, scaling relation works surprisingly well at RHIC
- Different quark masses:
  - new feature in  $v_2(p_t)$
- For hadrons with narrow wavefunctions:
  - see quark  $v_2(p_t)$  from hadron  $v_2(p_t)$
- *If  $v_2$  scaling relation works for all identified hadrons*
  - *the most direct demonstration of a parton system ( $\sim QGP$ )*

*This talk is available at  
<http://nt4.phys.columbia.edu/people/zlin/publications/>*

